Phased Array Antennas

for Space Applications and Challenges

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Abstract

Phased array antennas are becoming increasingly popular in satellite communications because of their inherent advantages of beam reconfigurability. In this talk we present an overview of modern phased array technology in communication satellites. The talk begins with a brief history of phased array antennas followed by its basic architecture and operating principle. We then briefly discuss various applications of phased array antennas including target identification and communication. Performance comparison between array-fed reflector and direct radiating array is presented next. Methods for aperture analysis and beam synthesis are discussed. Different types of beam forming networks are shown and their operating principles are explained. The talk ends with a discussion of design challenges for radiating elements, active components and beam forming networks.

Index Terms:
Phased Array, beam forming network, array-fed reflector, aperture analysis, synthesis

Biography

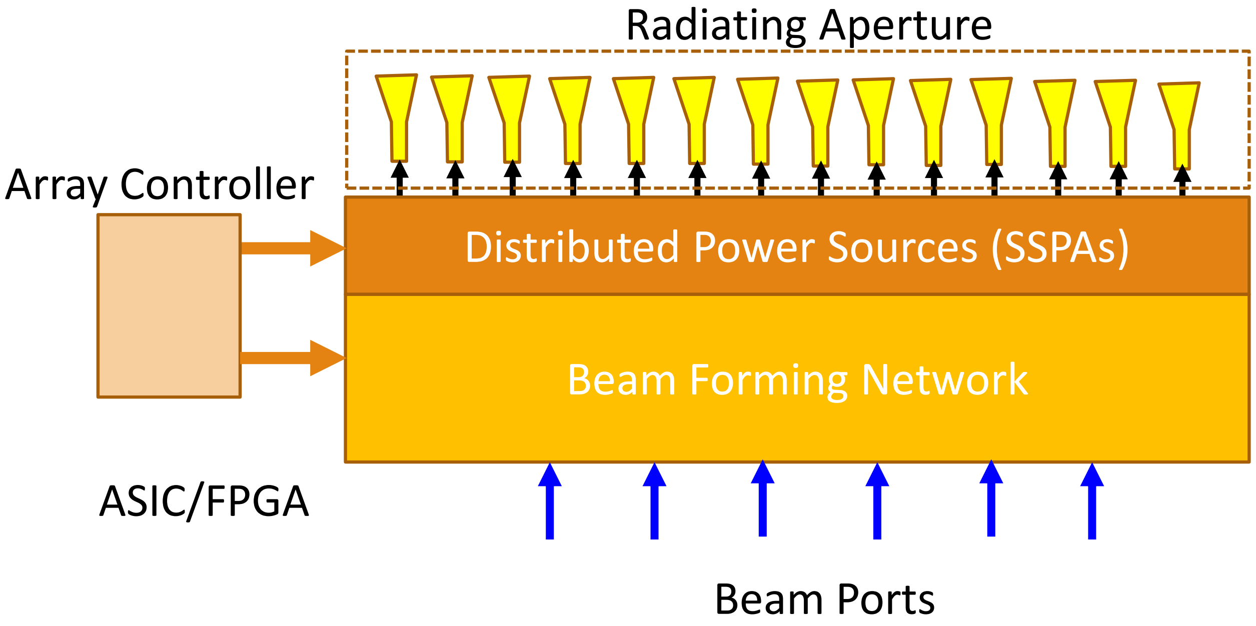
Arun K. Bhattacharyya received his B.Eng. degree in electronics and telecommunication engineering from Bengal Engineering College, University of Calcutta in 1980, and the M.Tech. and Ph.D. degrees from Indian Institute of Technology, Kharagpur, India, in 1982 and 1985, respectively.

From November 1985 to April 1987, he was with the University of Manitoba, Canada, as a Postdoctoral Fellow in the electrical engineering department. From May 1987 to October 1987, he worked for Til-Tek Limited, Kemptville, Ontario, Canada as a senior antenna engineer. In October 1987, he joined the University of Saskatchewan, Canada as an assistant professor of electrical engineering department and then promoted to the associate professor rank in 1990. In July 1991 he joined Boeing Satellite Systems (formerly Hughes Space and Communications), Los Angeles as a senior staff engineer, and then promoted to scientist and senior scientist ranks in 1994 and 1998, respectively. Dr. Bhattacharyya became a Technical Fellow of Boeing in 2002. In September 2003 he joined Northrop Grumman Space Technology group as a staff scientist and then became Distinguished Engineer and Engineering Fellow at Northrop Grumman. At present he is with the RF Center of Excellence of Lockheed Martin Corporation and working as a Principal Engineer/Scientist. He is the author of “Electromagnetic Fields in Multilayered Structures-Theory and Applications”, Artech House, Norwood, MA, 1994 and “Phased Array Antennas, Floquet Analysis, Synthesis, BFNs and Active Array Systems”, John Wiley, 2006. He authored over 100 technical papers, 5 book-chapters and has 19 issued patents. His technical interests include electromagnetics, printed antennas, multilayered structures, active phased arrays and modeling of microwave components and circuits.

Dr. Bhattacharyya became a Fellow of IEEE in 2002. He was a Distinguished Lecturer of IEEE APS society from 2011 to 2014. He served as an associate editor of IEEE Transaction Antennas and Propagation from 2012to 2016. Dr. Bhattacharyya is a recipient of numerous awards including the 1996 Hughes Technical Excellence Award, 2002 Boeing Special Invention Award for his invention of “High Efficiency horns”, 2003 Boeing Satellite Systems Patent Awards, 2005 Tim Hannemann Annual Quality Award and 2007 Distinguished Engineer award at Northrop Grumman Space Technology.

Phased Array Architecture

Array Architecture: 3 major blocks



Radiating Aperture

Array Controller

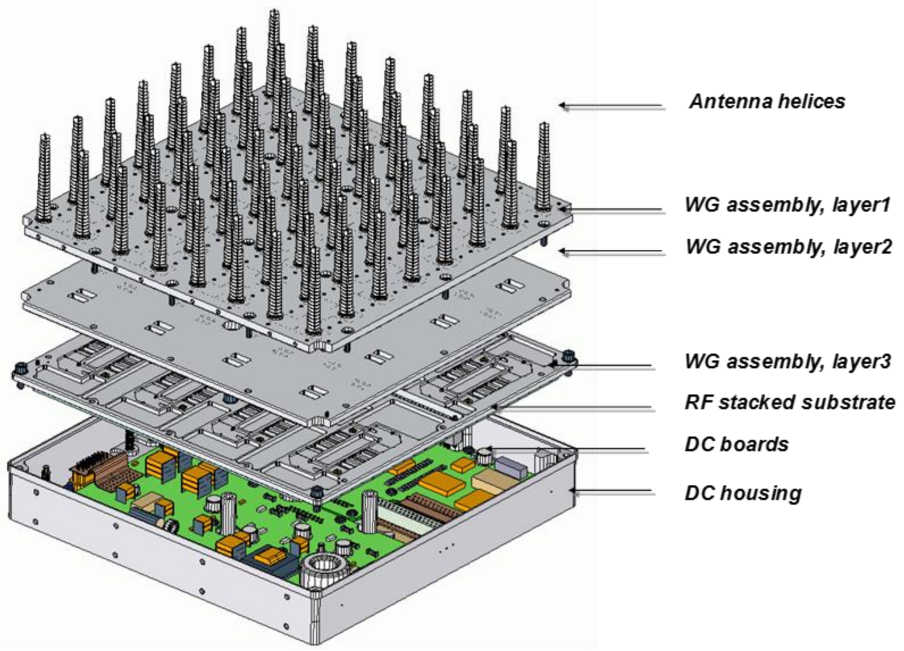
Distributed Power Sources (SSPAs)

Beam Forming Network

ASIC/FPGA

Beam Ports

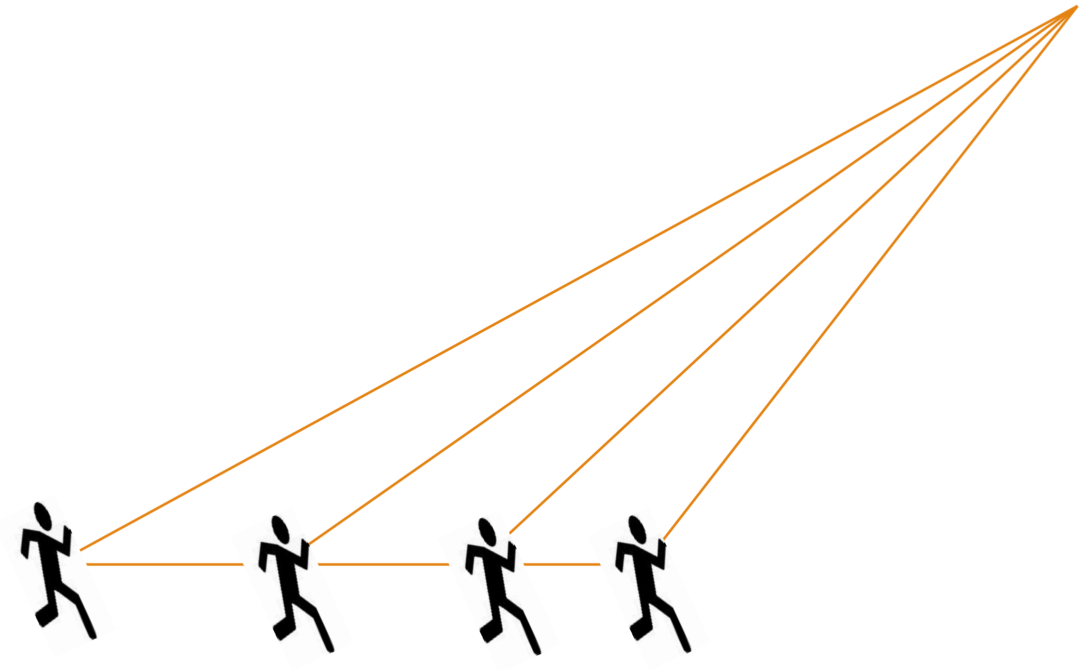
20 GHz Array (Lier et al., APS Magazine 2009)


Antenna helices
WG assembly, layer1
WG assembly, layer2
WG assembly, layer3
RF stacked substrate
DC boards
DC housing

ASIC: Application Specific Integrated Circuit
FPGA: Field Programmable Gate Array

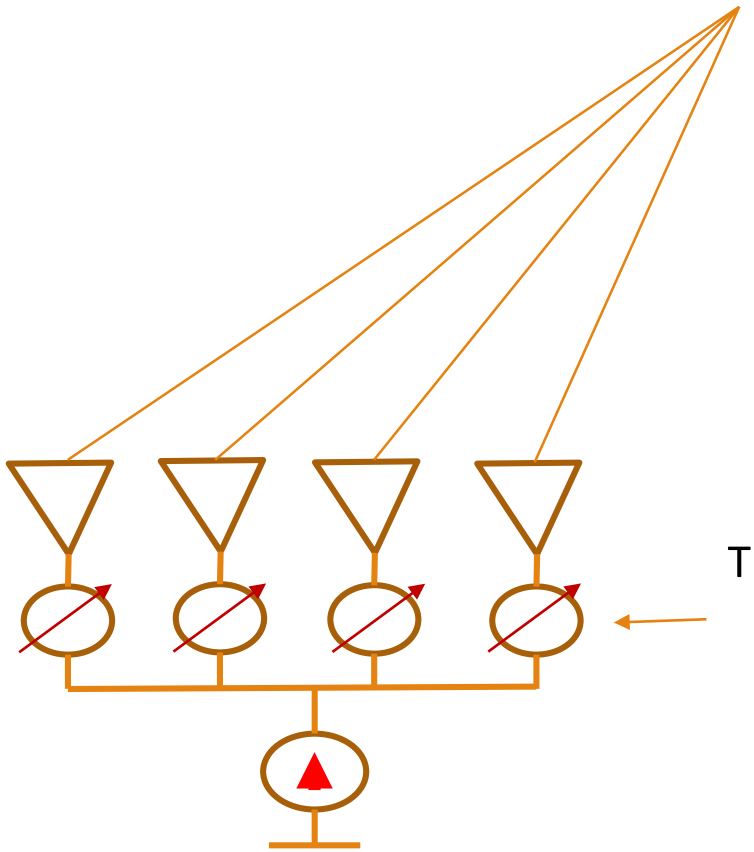
How does a Phased Array work?

Objective: Maximizing RF signal strength



Early Starter

Late Starter



Time delay units
or
Phase shifters

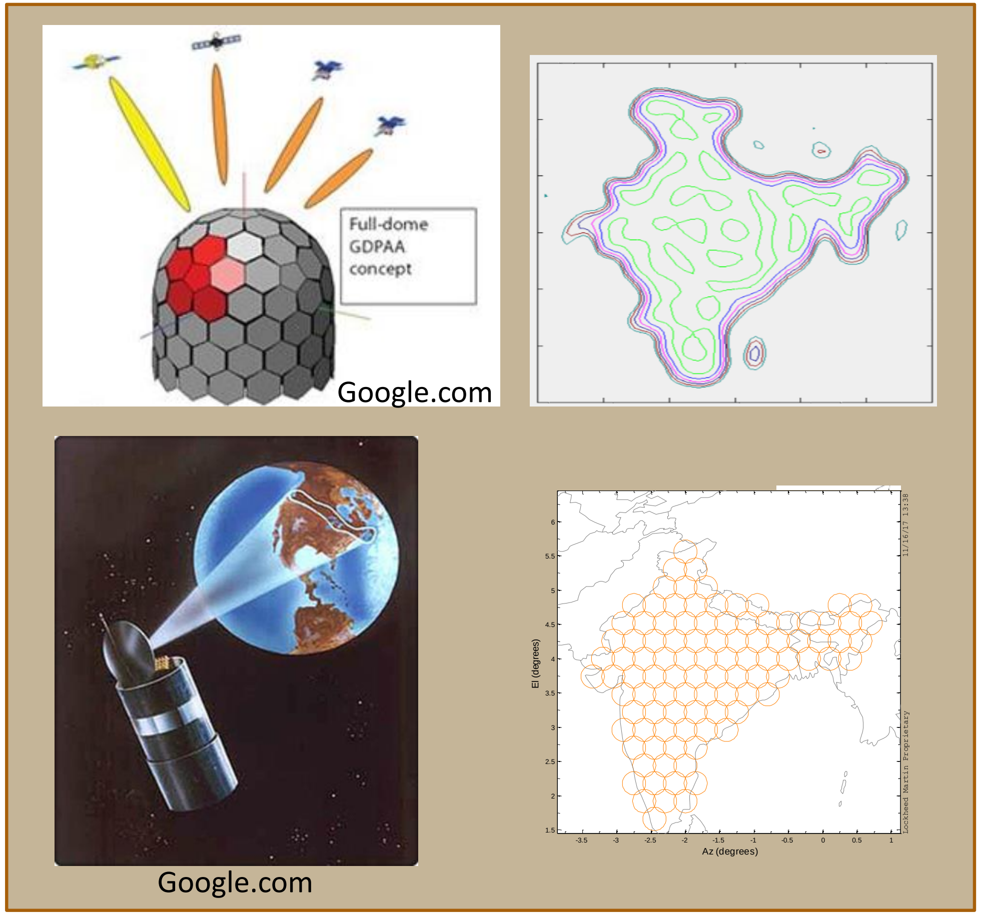
Applications of Phased Arrays

Target identification and detection (RADAR):

- Pencil beams with Low side-lobes to avoid clutters

Satellite Communication

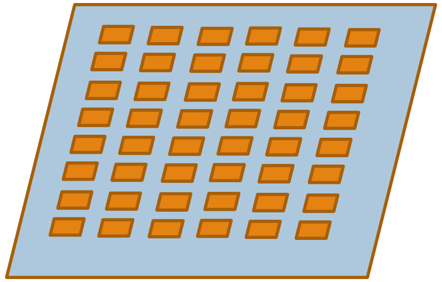
- Broadcast (TV, Radio): Shaped beams
- Cellular communication: Multiple Spot beams with good C/I

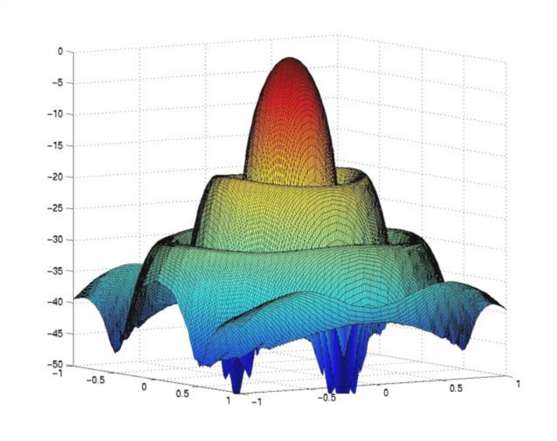

Full-dome
GDPAA
concept
El (degrees)
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
-3.5
-3
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
Az (degrees)
11/16/17 13:38
Lockheed Martin Proprietary

Google.com

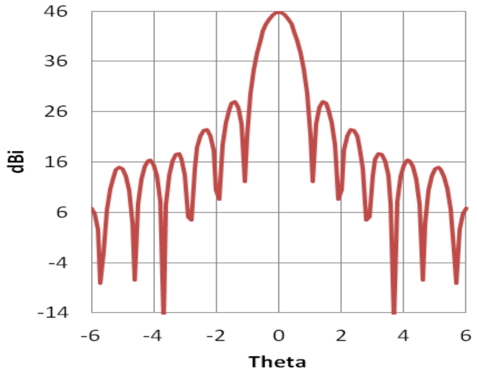
Google.com

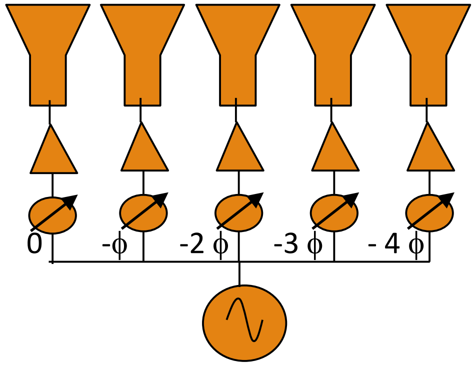
Scanned Pencil Beam (RADAR)





Max power at one point

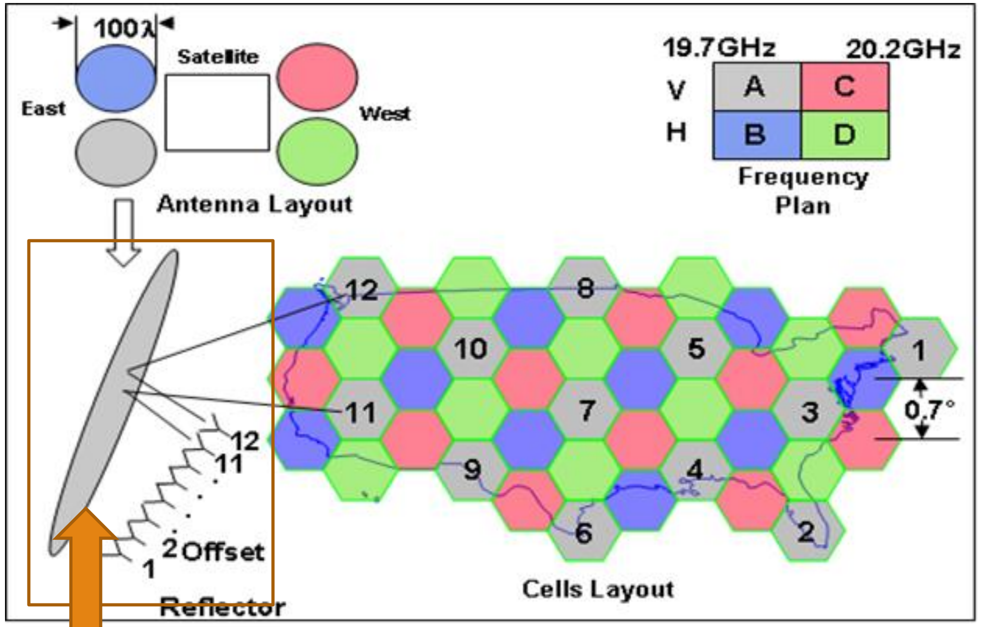


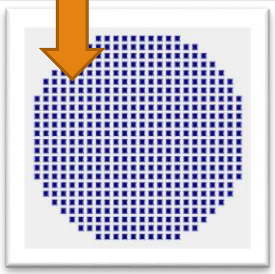


- Linear phase shift for array elements
- Amplitude distribution based on Side-lobe levels
- Amplitude distribution can be synthesized analytically
- Mostly used distributions: Chebyshev, Taylor, Gaussian

Multiple Spot-Beam Array

- For cellular applications
- Narrow Flat-top beams
- Multi-color reuse scheme to minimize adjacent beam interference
- Optimized for max C/I over co-color cells
- DRA is preferable over AFR for wide scan angle/covering far separated zones

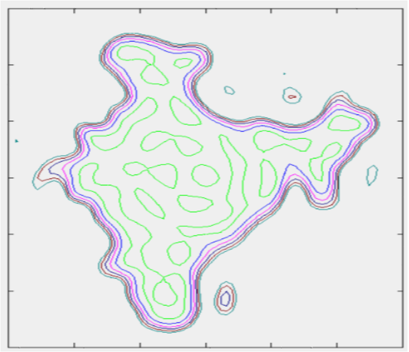

100λ
Satellite
East
West
Antenna Layout
19.7GHz
20.2GHz
V
H
A
C
B
D
Frequency Plan
12
8
10
5
1
11
7
3
0.7°
9
4
6
2
12
11
2
1
Offset
Reflector
Cells Layout

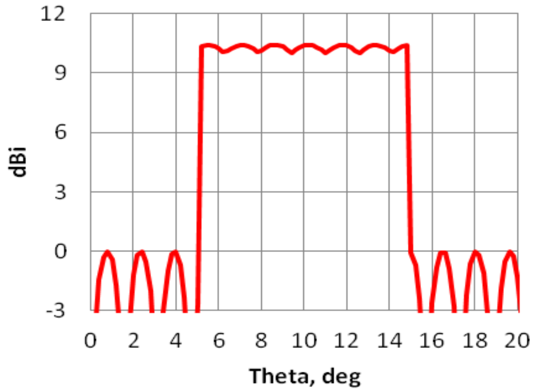


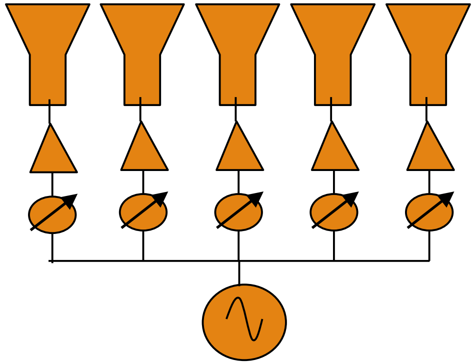
Bhattacharyya, Goyette, IEEE 2004

Shaped Beams Array (Broadcasting)

Shaped Beam (**Uniform power distribution in a region**)

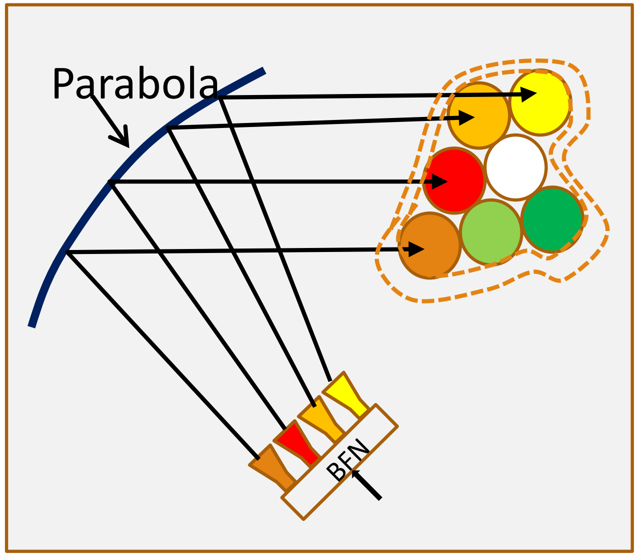


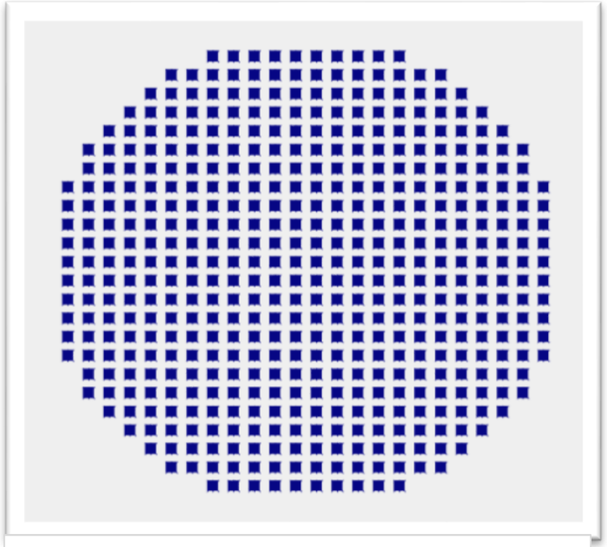




- Uniform power distribution inside a region
- Non-linear phase distribution
- Analytical solution is not possible
- Several algorithms are available

Array-Fed Reflector Versus Phased Array



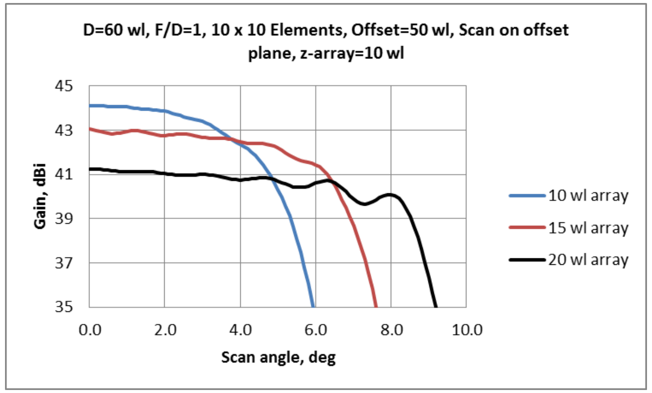


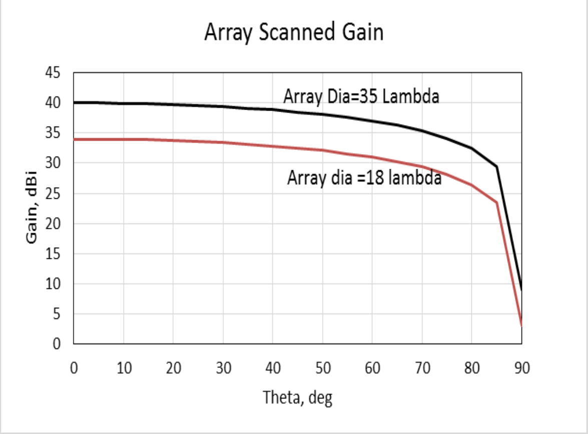
A-F Reflector:

- Small array size
- Low scan/Limited re-configurability.
- Typically **one contour beam** because of high scan loss

Phased array:

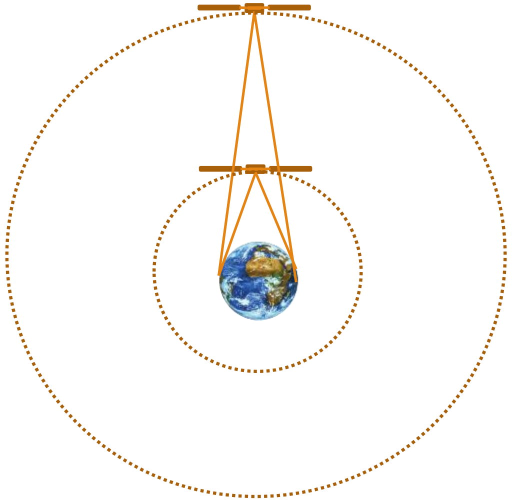
- Wide-angle scan/Fully reconfigurable
- Can create **multiple contour beams** in a wide angular range
- High implementation Cost

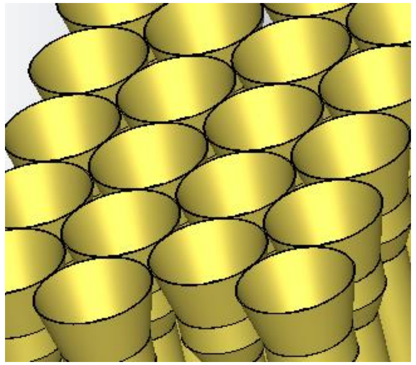


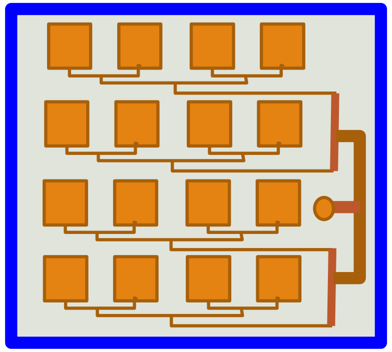


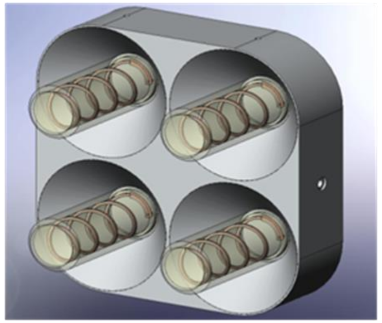
Radiating Elements

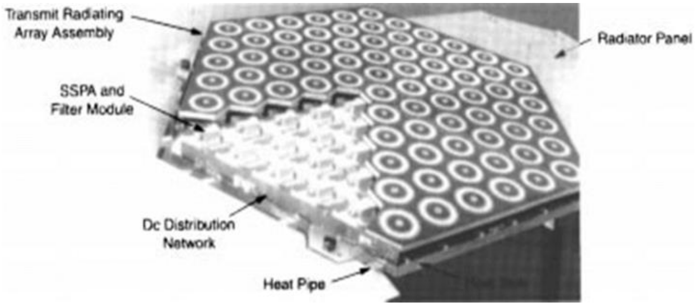
- Narrow band narrow scan
  - Horn/Patch/Helix/Cup dipole
- Wide-band narrow scan
  - Vivaldi/Ridge horn
- Narrow band/wide scan
  - Patch/Ring-slot
- Wide-band wide scan
  - Tapered slot/Modified Vivaldi/ Notch/Current sheet (Bow-Tie)



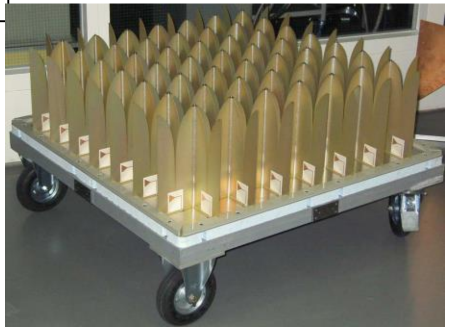




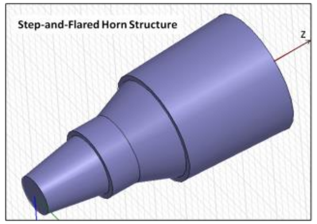



Transmit Radiating Array Assembly
Radiator Panel
SSPA and Filter Module
Dc Distribution Network
Heat Pipe

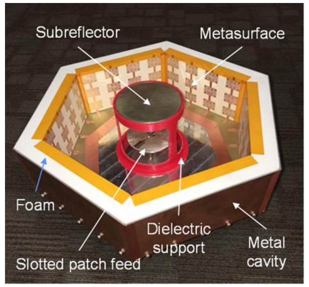
Dietrich et al., IEEE TAP June 1998. © 1998 IEEE



Ref: Maaskant et al, IEEE TAP June 2011. © 2011 IEEE


Step-and-Flared Horn Structure
z

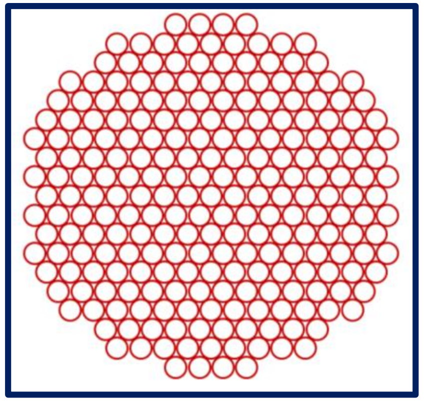
Bhattacharyya,Goyete/Artech House

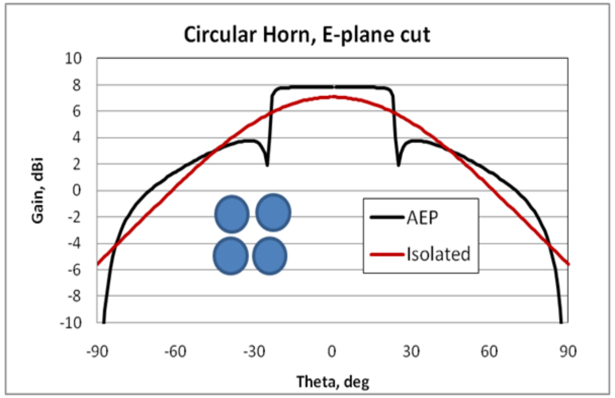

Subreflector
Metasurface
Foam
Dielectric support
Metal cavity
Slotted patch feed

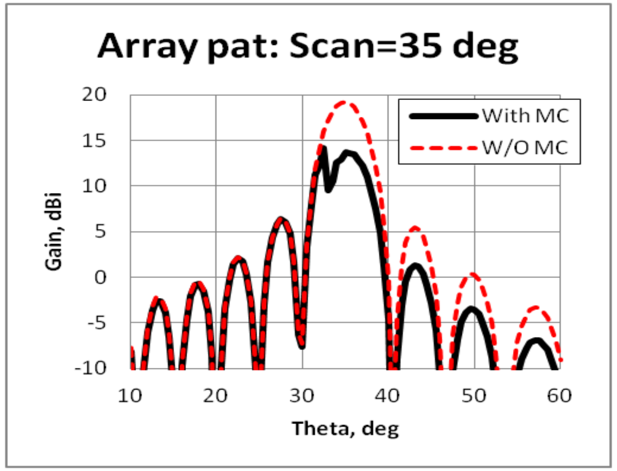
LMC

Array Analysis and Synthesis

Aperture Analysis







The "isolated" element pattern and element pattern in "array environment" are different. **This is generally true for small element spacing (less than one lambda).**

Consequently, the array patterns with and without mutual coupling are very different (about 5 dB gain difference in the main lobe region plus a blind spot)

Floquet analysis is critical for wide-angle scanned array

Beam Shaping Algorithms

Challenge:

To determine amplitude and phase distributions of the array elements with respect to a given shaped beam

ITERATIVE

Gradient Search

- Most versatile
- Minimizes a cost function

Conjugate Match

- Only applicable for array opt
- No explicit cost function
- Improves the lowest gain point

Projection Matrix Algorithm

EVOLUTIONARY

Genetic Algorithm (GA)

- Survival of the fittest
- Slow

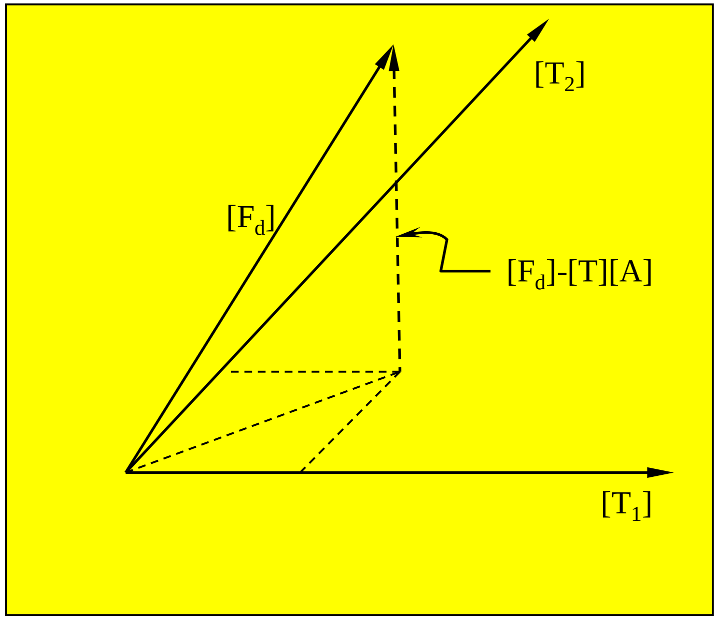
Particle Swarm

- Faster than conventional GA

Projection Matrix Algorithm

- Concept of vector space is invoked
- Error vector is orthogonal to the best-fit solution vector
- The projection matrix operator eliminates orthogonal error

$[F_d]=[T][A]$
$[A]$=Unknown
$[T]$=Known
$[F_d]$=“Semi” known

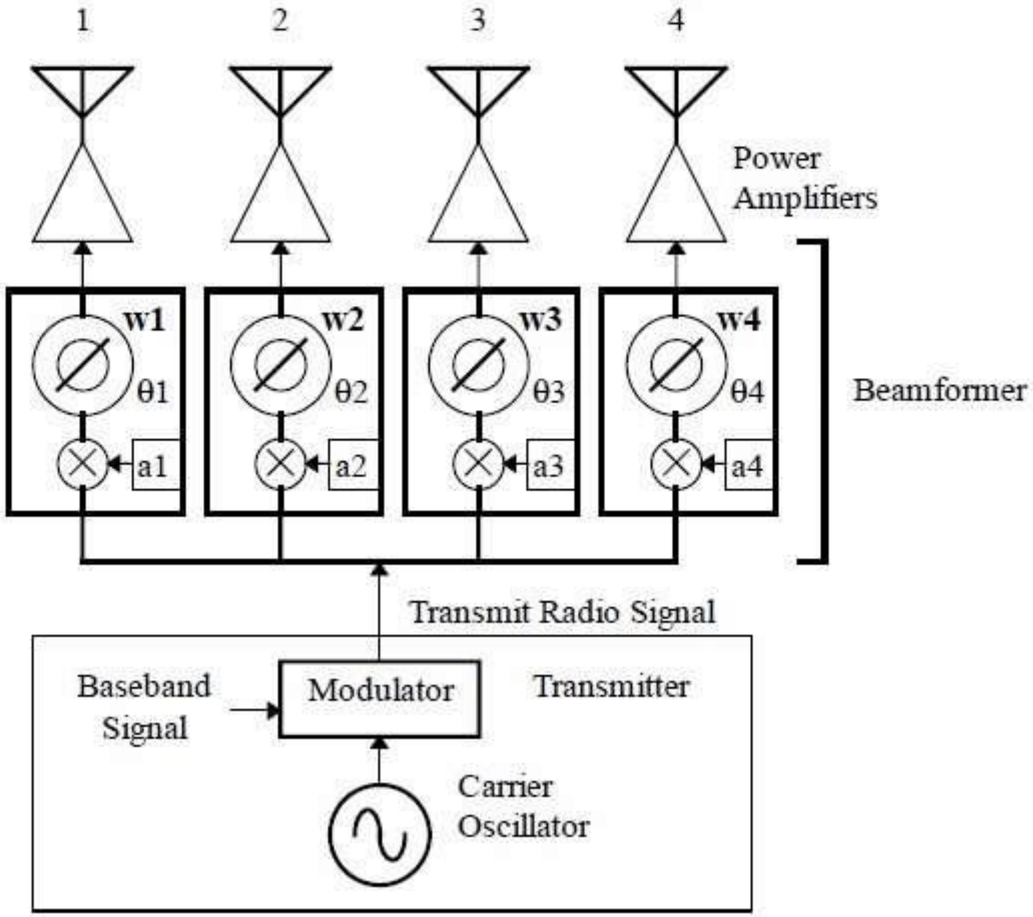


An ill-posed problem if $[F_d]$ does not lie on $[T_1]$-$[T_2]$ plane

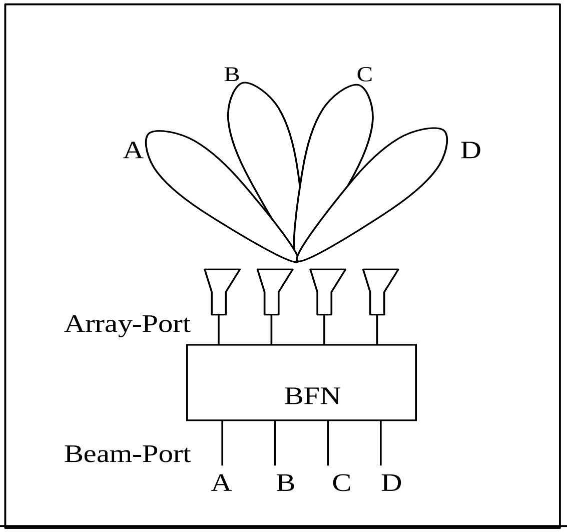
Beam Forming Network (BFN)

Analog Beamforming

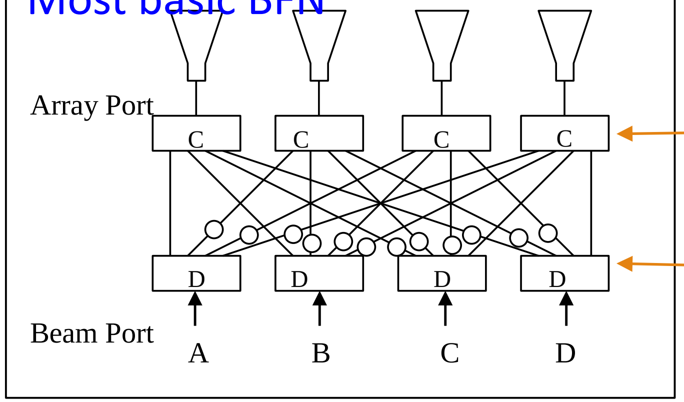
Schematic


1
2
3
4
Power Amplifiers
w1
w2
w3
w4
θ1
θ2
θ3
θ4
a1
a2
a3
a4
Beamformer
Transmit Radio Signal
Baseband Signal
Modulator
Transmitter
Carrier Oscillator

Multiple beams implementation


B
C
A
D
Array-Port
BFN
Beam-Port
A
B
C
D

Most basic BFN

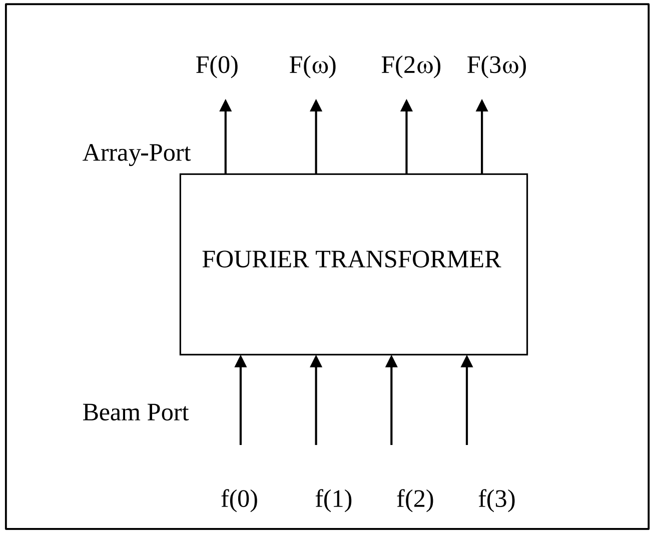

Array Port
C
C
C
C
D
D
D
D
Beam Port
A
B
C
D

Combiner

Divider

Butler Matrix

Based on FFT Algorithm


F(0)
F(ω)
F(2ω)
F(3ω)
Array-Port
FOURIER TRANSFORMER
Beam Port
f(0)
f(1)
f(2)
f(3)

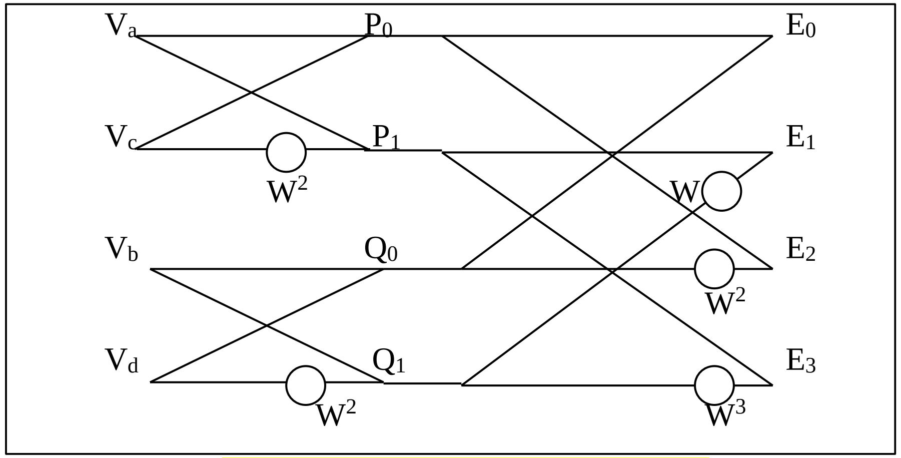
$$F(\omega) = f(0) + f(1)\exp(-j\omega) + f(2)\exp(-2j\omega) + f(3)\exp(-3j\omega)$$

ω = phase angle

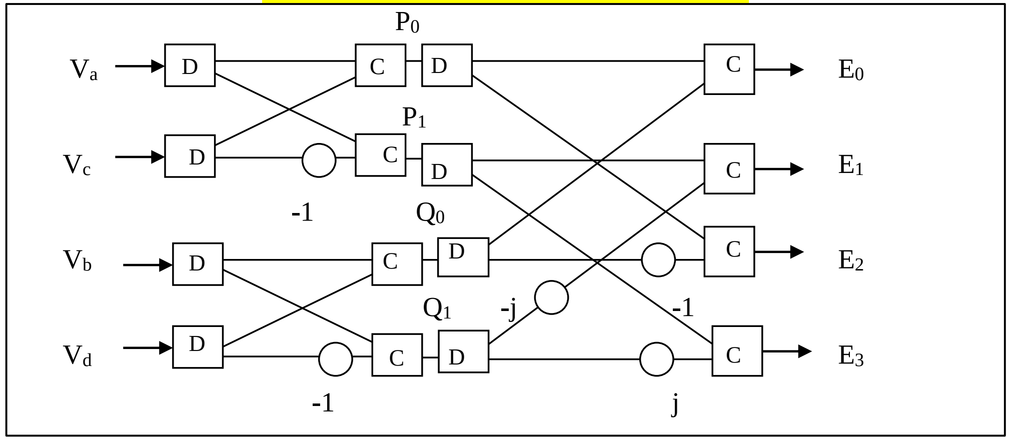
For 2^m beams

- Butler matrix BFN requires 2^m x (m-1)+1 phase shifters.
- Generic BFN requires 2^m x (2m-1) phase shifters

Graphical Representation of FFT


V_a
P_0
E_0
V_c
P_1
E_1
W^2
W
V_b
Q_0
E_2
W^2
V_d
Q_1
E_3
W^2
W^3

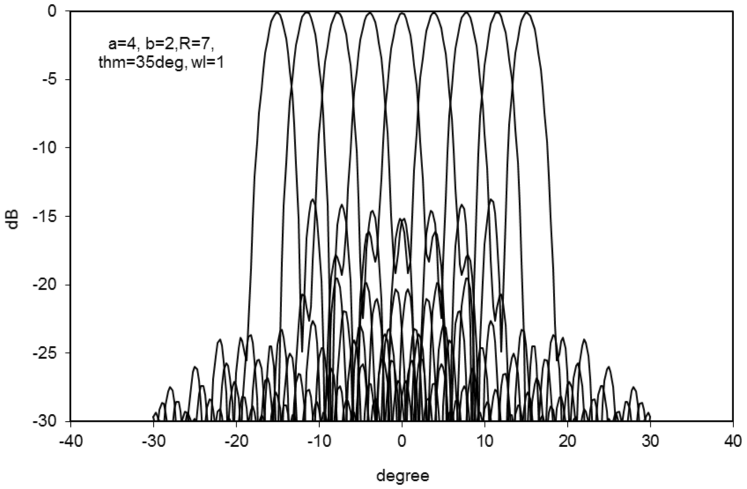
Implementation of FFT

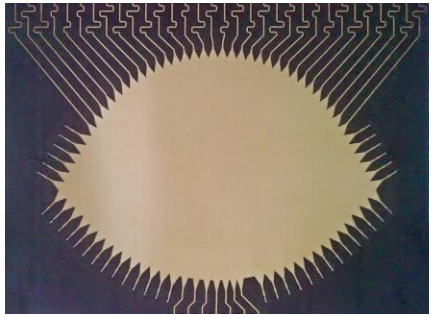

P_0
V_a
D
C
D
C
E_0
P_1
V_c
D
C
D
C
E_1
-1
Q_0
V_b
D
C
D
C
E_2
Q_1
-j
-1
V_d
D
C
D
C
E_3
-1
j

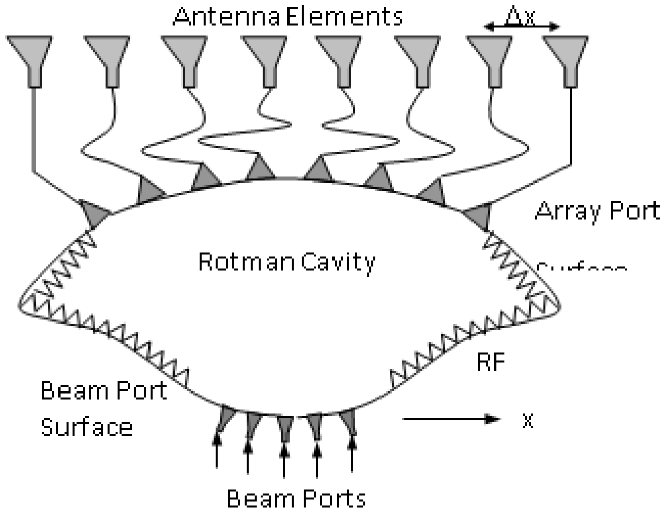
Rotman Lens

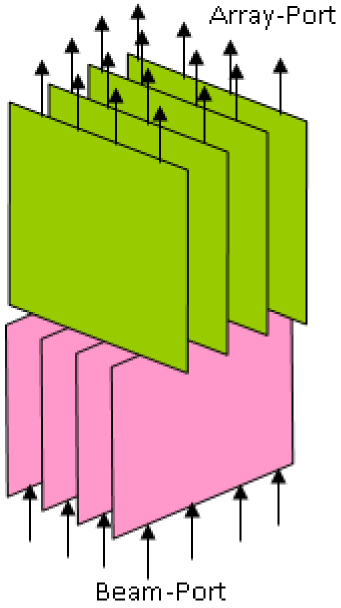
BFN without phase-shifter

- For multiple fixed beams
- Wide-band performance
- True Time Delay BFN
- Lower loss compared with
  MMIC phase-shifter based BFN
- Larger Mass






Antenna Elements
Δx
Array Port
Surface
Rotman Cavity
RF
Beam Port
Surface
X
Beam Ports


Array-Port
Beam-Port

Digital Beamforming Schematic

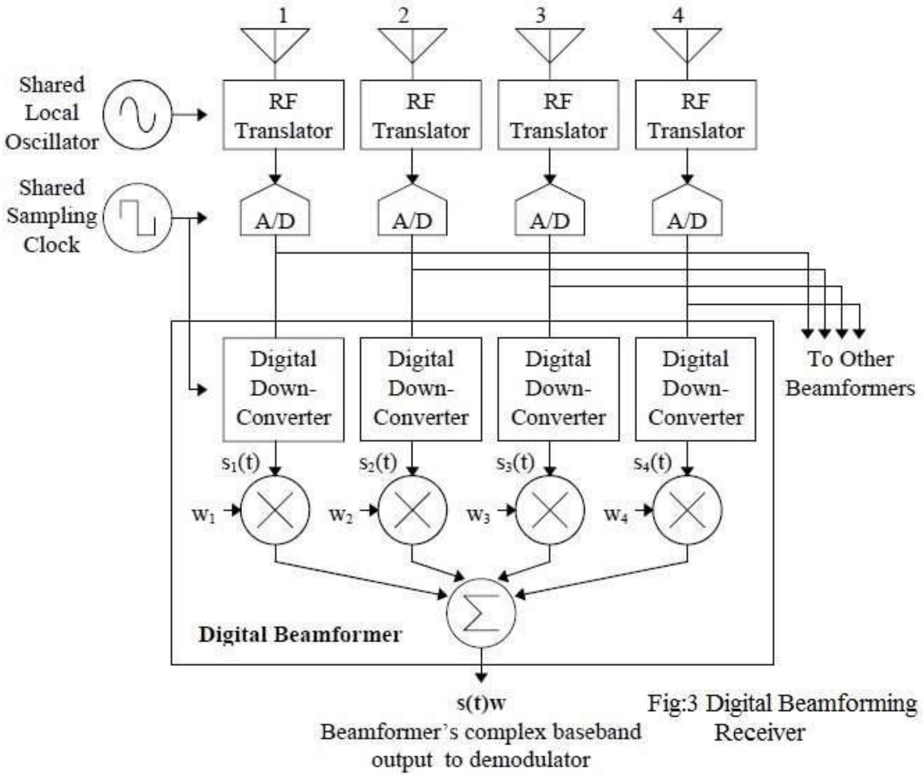
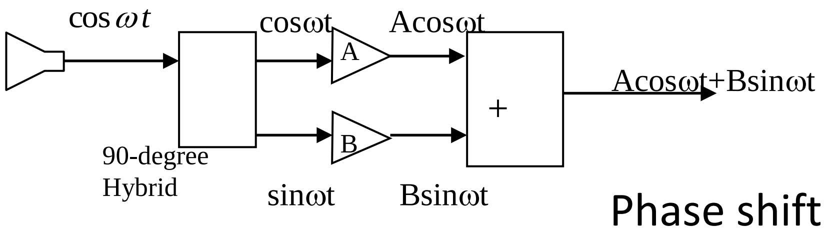

1
2
3
4
Shared Local Oscillator
Shared Sampling Clock
RF Translator
RF Translator
RF Translator
RF Translator
A/D
A/D
A/D
A/D
To Other Beamformers
Digital Down-Converter
Digital Down-Converter
Digital Down-Converter
Digital Down-Converter
s₁(t)
s₂(t)
s₃(t)
s₄(t)
w₁
w₂
w₃
w₄
Digital Beamformer
s(t)w
Beamformer's complex baseband output to demodulator

Fig:3 Digital Beamforming Receiver

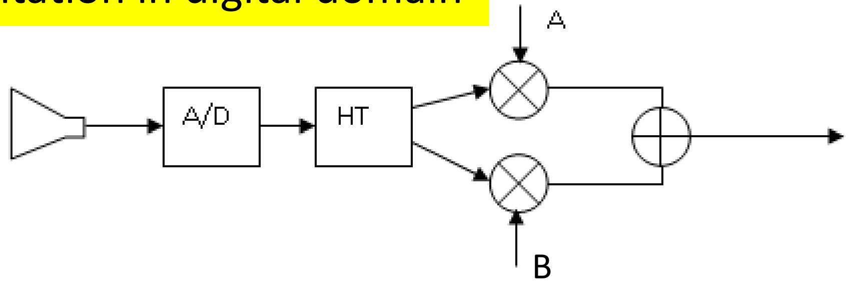
M=Number of multiplication/sec ~ 2 x BW x N
For 400 elements, 10MHz BW, M=8000 Mops

Principle of Phase-shift


cos ωt
90-degree Hybrid
cosωt
sinωt
A
B
Acosωt
Bsinωt
+
Acosωt+Bsinωt

Phase shift= $\tan^{-1}(B/A)$

Implementation in digital domain

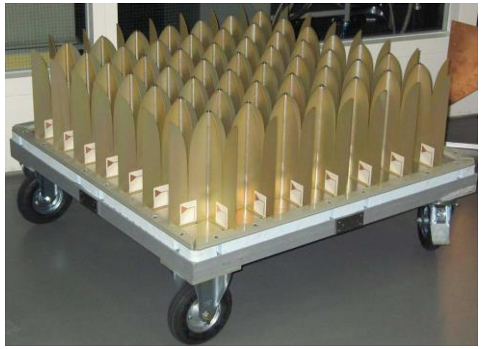


HT= Hilbert Transformation

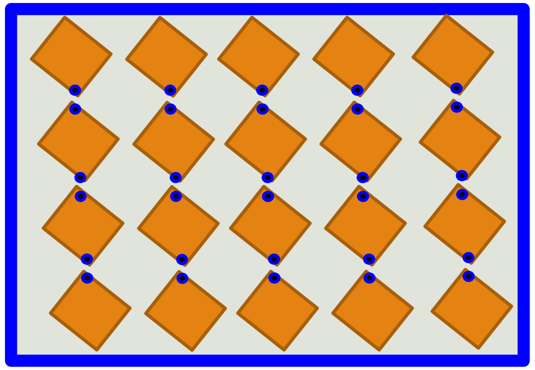
$$\sin\omega t = \frac{1}{\pi}\int_{-\infty}^{\infty}\frac{\cos\omega\tau}{(t-\tau)}d\tau$$

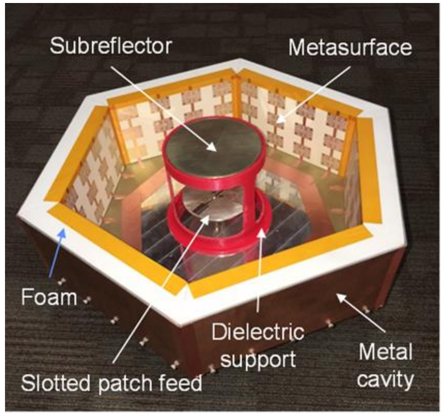
Challenges: Radiating Element

- Wide-band radiating elements
  - Vivaldi/Notch Type: Cross-pol issues at high scan angle
  - Self Complementary Type: Bow-Tie elements
    - Low aperture efficiency w/o Ground plane but very Wide-bandwidth
    - Excitation needs BALUN
  - Meta-surface backed elements
    - Lossy due to magnetic material

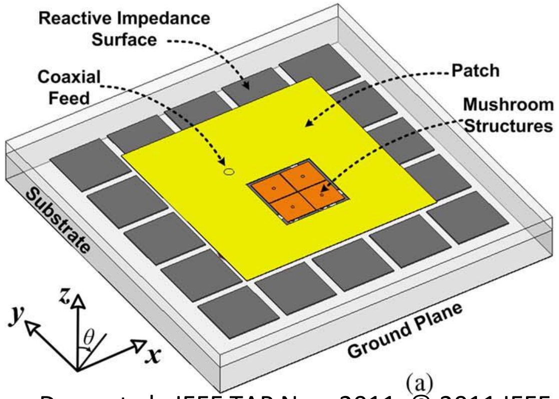


Ref: Maaskant et al, IEEE TAP June 2011. © 2011 IEEE




Subreflector
Metasurface
Foam
Dielectric support
Metal cavity
Slotted patch feed

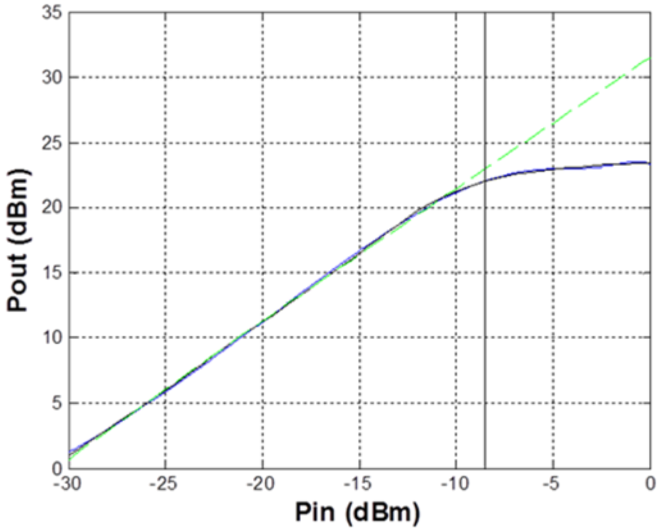
Lier-Radiator


Reactive Impedance Surface
Coaxial Feed
Patch
Mushroom Structures
Substrate
Ground Plane
z
y
x
θ
(a)

Dong et al., IEEE TAP Nov. 2011. © 2011 IEEE

BFN and SSPA Challenges

- Issues with Analog BFNs
  - BFN with MMIC phase shifters have limited scan bandwidth
  - MMIC phase shifters are lossy
  - TTD units improve the bandwidth
  - Rotman Lenses have lower loss than MMIC
- SSPA Challenges
  - Power Added Efficiency
  - Gain Linearity: Minimize Intermod and NPR
- Digital BFNs
  - To increase the capacity of a satellite the instantaneous bandwidth should be high. This requires fast digital processor.



Concluding Remarks

Although the concept of phased array is about a century old (1905) but the practical realization started much later (1940). Commercially Phased array antennas were not attractive due to its high implementation cost. With the recent advancement of solid state technology and fabrication process the phased array antennas are becoming cost effective and gaining importance due to many flexibilities it offers compared with Reflector antennas.